

Supporting Online Material

Contribution of seasonal sub-Antarctic surface water variability to millennial-scale changes in atmospheric CO₂ over the last deglaciation and Marine Isotope Stage 3

Julia Gottschalk¹, Luke C. Skinner¹, Claire Waelbroeck²

Corresponding Author: J. Gottschalk (jg619@cam.ac.uk, +44 (0) 1223 768342)

¹Godwin Laboratory for Palaeoclimate Research, Department of Earth Sciences, University of Cambridge, Cambridge CB2 3EQ, UK

²LSCE/IPSL Laboratoire, CNRS-CEA-UVSQ, 91198 Gif-sur-Yvette, France

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1. Compilation of South Atlantic core-top $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ of *G. bulloides* and *N. pachyderma* (s.)

The planktonic $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ data compilation includes a number of published (Duplessy et al., 1991; Keigwin and Boyle, 1989; Kohfeld et al., 2000; Mulitza et al., 1997; Niebler, 1995; Niebler et al., 1999) and unpublished (Hubberten and Niebler, pers. comm.) data sets. Unpublished data are listed in Table S1.

To minimize a potential bias of the planktonic $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ compilation by size fraction variations (Niebler et al., 1999; Oppo and Fairbanks, 1989), we have omitted data obtained from very small (<200 μm) and very big (>315 μm) size fractions, where documentation for the data was available. The size fractions included in the compilation of planktonic $\delta^{13}\text{C}$ (200-250 μm and 250-315 μm) are therefore similar to those of our down-core analyses. However, information on the measured size fraction was not available for a large portion of the planktonic $\delta^{18}\text{O}$ dataset, which may partly explain the large variability of the planktonic $\delta^{18}\text{O}$ data (Fig. 3). We have therefore calculated a latitudinal (2°-running) mean (as well as the corresponding \pm one sigma variability), which reduces the bias likely caused by measurements on different size fractions and allows a comparison to hydrographic data of the proposed modern foraminiferal habitats to be made.

2. Age model MD07-3076Q

Age-depth markers that result from splicing the radiocarbon- and *N. pachyderma* (s.) abundance-based chronologies are given in Table S2. The final chronology is based on a linear interpolation between these tiepoints.

Age uncertainties of the *N. pachyderma* (s.)-based chronology (Fig. S1) may result from the choice of the reference ice core temperature record (e.g. EPICA Dome C (EDC) δD versus EPICA Dronning-Maud-Land (EDML) $\delta^{18}\text{O}$) and different alignment approaches (tiepoints in maximum versus transitional phases of Antarctic temperature change). We have assessed this uncertainty by calculating the maximum 95% highest posterior density region (Fig. S1) resulting from the individual alignment approaches with the Bayesian statistical software BChron (Haslett and Parnell, 2008). The resulting

mean age uncertainty of the *N. pachyderma* (s.) abundance-based chronology amounts to 1600 ± 500 years. The outcome of this study does not depend on the choice of the reference Antarctic temperature record.

3. Gas age scales of CO₂ records from Antarctic ice cores

Deglacial CO_{2,atm} data of the BYRD (Neftel et al., 1988; Staffelbach et al., 1991) and Siple Dome (Ahn et al., 2004) ice cores are reported on the GICC05 gas age scale obtained by Pedro et al., (2012). The age scales are based on a methane synchronization of BYRD to the Greenland ice cores (Blunier and Brook, 2001; Brook et al., 2005). The EDC1 age scale of deglacial CO_{2,atm} data obtained from the EDC ice core (Monnin et al., 2001) has been converted to the AICC2012 gas age scale using the depth-gas age relation obtained by Veres et al., (2013).

Gas ages of CO_{2,atm} reconstructed for the last glacial cycle from BYRD (Ahn and Brook, 2008; Ahn et al., 2012) have been transferred to the AICC2012 age scale by CH₄ synchronization of BYRD and EDML (Blunier and Brook, 2001; EPICA Community Members, 2006), whereby the methane record of EDML has been transferred to the AICC2012 gas age scale according to the depth-gas age constraints of Veres et al., (2013). EDML1_sc4 gas ages for CO_{2,atm} data of the Talos Dome (Bereiter et al., 2012) and EDML (Bereiter et al., 2012; Lüthi et al., 2010) ice cores have been similarly adjusted to AICC2012 gas ages (Veres et al., 2013). The GT4 Vostok age scale of CO_{2,atm} data reported from Taylor Dome (Indermühle et al., 2000) have been converted to AICC2012 gas ages according to the depth-gas age constraints in the Vostok ice core by Veres et al., (2013). CO₂ data from the Siple Dome ice core (Ahn and Brook, 2014) are shown on the GICC05 age scale reported by Ahn and Brook, (2014).

The relative timing of the adapted gas age scales of the various CO_{2,atm} records has been checked by applying the same gas ages scale to the respective methane records of the BYRD (Blunier and Brook, 2001), Siple Dome (Ahn and Brook, 2014; Brook et al., 2005), EDC (Monnin et al., 2001), EDML (EPICA Community Members, 2006), Taylor Dome (Brook et al., 2000) and Talos Dome (Buiron et

al., 2012) ice cores. The adjusted gas age scales agree well within centuries (Fig. S2). Mean CO_{2,atm} changes have been calculated by averaging all available CO_{2,atm} data interpolated on a common, 100 year-spaced time scale (Fig. S2).

4. Correction of planktonic foraminifer $\delta^{13}\text{C}$

Planktonic foraminifer $\delta^{13}\text{C}$ ($\delta^{13}\text{C}_{\text{shell}}$) have been corrected for the temperature (T), carbonate ion (CO_3^{2-}) and dietary (i.e. particulate organic matter, POM) $\delta^{13}\text{C}$ effects according to the procedure outlined in Kohfeld et al., (2000) applying equation 1.

$$\delta^{13}\text{C}_{\text{eq}} = \delta^{13}\text{C}_{\text{shell}} + 0.13 T + 0.013 [\text{CO}_3^{2-}] - 0.084 \delta^{13}\text{C}_{\text{POM}} + B_{\text{tot}} \quad (1)$$

An adjustment constant B_{tot} of -2.3 and -2.9 has been applied for the corrections of *G. bulloides* and *N. pachyderma* (s.) $\delta^{13}\text{C}_{\text{shell}}$, respectively. Our applied B_{tot} for correcting *N. pachyderma* (s.) $\delta^{13}\text{C}$ agrees well with the applied value of -2.8 reported by Kohfeld et al., (2000). The stable carbon isotopic composition of the foraminiferal diet has been approximated by $\delta^{13}\text{C}$ of POM reported by Goericke and Fry, (1994). Temperatures used for the correction of *G. bulloides* $\delta^{13}\text{C}$ have been extracted from the World Ocean Atlas 2009 (Locarnini et al., 2010) and are taken to be spring and summer temperatures averaged over the water depth intervals 0-100 m north and south of the PF, respectively. Temperatures to correct *N. pachyderma* (s.) $\delta^{13}\text{C}$ refer to summer surface temperatures averaged over the water levels 0-100 m and 50-150 m north and south of the PF, respectively. Mean annual CO_3^{2-} concentrations have been used for the correction of planktonic $\delta^{13}\text{C}$ and have been computed from the GLODAP data set (Key et al., 2004) using the CO₂SYS program (Lewis and Wallace, 1998). Mean annual CO_3^{2-} concentrations averaged over a water depth of 0-100 m have been applied to represent the near-surface habitats of *G. bulloides* and *N. pachyderma* (s.), and CO_3^{2-} data averaged over a water depth of 50-150 m has been selected to represent the ‘sub-surface’ habitat of *N. pachyderma* (s.) south of the PF. The temperature and CO_3^{2-} data used for the corrections have been obtained along 20°W.

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Table S1. *G. bulloides* $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ of core-top sediments in the South Atlantic obtained by H.-W. Hubberten and H.-S. Niebler (Alfred-Wegener-Institute, Germany)

Location	Latitude	Longitude	Elevation (m)	$\delta^{18}\text{O}$ (permil PDB)	$\delta^{13}\text{C}$ (permil PDB)	Fraction
PS1759-1	-50.165	5.755	-3793	3.234	0.705	250-315 μm
PS1759-1	-50.165	5.755	-3793	3.173	0.219	200-250 μm
PS1775-5	-50.952	-7.503	-2523	3.271	0.417	250-315 μm
PS1779-3	-50.3992	-14.0803	-3574	3.031	0.682	250-315 μm
PS1779-3	-50.3992	-14.0803	-3574	3.081	0.454	200-250 μm
PS2103-2	-51.3292	-3.3243	-2947	2.566	0.337	250-315 μm
PS2103-2	-51.3292	-3.3243	-2947	2.469	-0.042	200-250 μm
PS2104-1	-50.7425	-3.2118	-2592	3.176	0.472	250-315 μm
PS2341-1	-55.6155	-57.6353	-4247	2.510	0.701	200-250 μm
PS2341-1	-55.6155	-57.6353	-4247	2.507	1.261	250-315 μm
PS2341-1	-55.6155	-57.6353	-4247	2.724	0.472	200-250 μm
PS2341-1	-55.6155	-57.6353	-4247	2.041	0.802	250-315 μm
PS2341-1	-55.6155	-57.6353	-4247	2.293	1.126	250-315 μm
PS2341-1	-55.6155	-57.6353	-4247	2.353	1.359	250-315 μm
PS2341-1	-55.6155	-57.6353	-4247	2.325	0.838	200-250 μm
PS2343-1	-55.165	-58.0917	-3281	2.217	0.563	250-315 μm
PS2343-1	-55.165	-58.0917	-3281	1.865	0.118	200-250 μm
PS2343-1	-55.165	-58.0917	-3281	1.898	0.059	200-250 μm
PS2343-1	-55.165	-58.0917	-3281	1.944	0.066	250-315 μm
PS2351-1	-53.765	-58.8867	-575	2.219	0.560	250-315 μm
PS2351-1	-53.765	-58.8867	-575	2.075	0.113	200-250 μm
PS2351-1	-53.765	-58.8867	-575	1.956	0.225	250-315 μm
PS2351-1	-53.765	-58.8867	-575	2.031	0.304	200-250 μm
PS2352-1	-53.7367	-58.9033	-1033	2.077	0.616	250-315 μm
PS2352-1	-53.7367	-58.9033	-1033	2.094	0.363	200-250 μm
PS2352-1	-53.7367	-58.9033	-1033	2.107	0.625	250-315 μm
PS2352-1	-53.7367	-58.9033	-1033	1.597	-0.121	200-250 μm
PS2353-1	-53.7367	-58.9033	-1033	2.613	0.559	250-315 μm
PS2353-1	-53.7367	-58.9033	-1033	2.116	0.426	200-250 μm
PS2353-2	-53.6067	-58.9767	-1916	1.691	0.230	200-250 μm
PS2353-2	-53.6067	-58.9767	-1916	2.126	0.664	250-315 μm

Table S2. Age-depth markers in MD07-3076Q obtained from calibrated radiocarbon dates and the stratigraphic alignment of abundance lows of *N. pachyderma* (s.) (%Nps) with maxima of the first derivative of the EDC δD record

Depth (cm)	Age (a BP)	Method ¹
1.5	1203	¹⁴ C, Skinner et al., 2010
5.5	1625	¹⁴ C, Skinner et al., 2010
9.5	2240	¹⁴ C, Skinner et al., 2010
15.5	3297	¹⁴ C, Skinner et al., 2010
21.5	4734	¹⁴ C, Skinner et al., 2010
25.5	5658	¹⁴ C, Skinner et al., 2010
31.5	6543	¹⁴ C, Skinner et al., 2010
35.5	7018	¹⁴ C, Skinner et al., 2010
41.5	8455	¹⁴ C, Skinner et al., 2010
45.5	9353	¹⁴ C, Skinner et al., 2010
49.5	10003	¹⁴ C, Skinner et al., 2010
53.5	10569	¹⁴ C, Skinner et al., 2010
55.5	10847	¹⁴ C, Skinner et al., 2010
59.5	11277	¹⁴ C, Skinner et al., 2010
61.5	11538	¹⁴ C, Skinner et al., 2010
63.5	11842	¹⁴ C, Skinner et al., 2010
67.5	12536	¹⁴ C, Skinner et al., 2010
73.5	13043	¹⁴ C, Skinner et al., 2010
77.5	13405	¹⁴ C, Skinner et al., 2010
85.5	14362	¹⁴ C, Skinner et al., 2010
89.5	14670	¹⁴ C, Skinner et al., 2010
91.5	14792	¹⁴ C, Skinner et al., 2010
95.5	14938	¹⁴ C, Skinner et al., 2010
99.5	15205	¹⁴ C, Skinner et al., 2010
109.5	16590	¹⁴ C, Skinner et al., 2010
113.5	17113	¹⁴ C, Skinner et al., 2010
117.5	17578	¹⁴ C, Skinner et al., 2010
119.5	17802	¹⁴ C, Skinner et al., 2010
121.5	18006	¹⁴ C, Skinner et al., 2010
125.5	18381	¹⁴ C, Skinner et al., 2010
133.5	19042	¹⁴ C, Skinner et al., 2010
137.5	19403	¹⁴ C, Skinner et al., 2010
145.5	20512	¹⁴ C, Skinner et al., 2010
161.5	22881	¹⁴ C, Skinner et al., 2010
173.5	24743	¹⁴ C, Skinner et al., 2010
187.5	26234	¹⁴ C, Skinner et al., 2010
197.5	27380	¹⁴ C, Skinner et al., 2010
232.0	30062	%Nps aligned to $\delta(\text{EDC } \delta D)/\delta t$ (this study)
294.9	34188	%Nps aligned to $\delta(\text{EDC } \delta D)/\delta t$ (this study)
333.7	36072	%Nps aligned to $\delta(\text{EDC } \delta D)/\delta t$ (this study)

380.5	39384	%Nps aligned to $\delta(\text{EDC } \delta\text{D})/\delta t$ (this study)
429.3	41680	%Nps aligned to $\delta(\text{EDC } \delta\text{D})/\delta t$ (this study)
459.1	43571	%Nps aligned to $\delta(\text{EDC } \delta\text{D})/\delta t$ (this study)
509.5	47004	%Nps aligned to $\delta(\text{EDC } \delta\text{D})/\delta t$ (this study)
606.5	54517	%Nps aligned to $\delta(\text{EDC } \delta\text{D})/\delta t$ (this study)
685.6	60002	%Nps aligned to $\delta(\text{EDC } \delta\text{D})/\delta t$ (this study)
739.8	65325	%Nps aligned to $\delta(\text{EDC } \delta\text{D})/\delta t$ (this study)
760.1	66741	%Nps aligned to $\delta(\text{EDC } \delta\text{D})/\delta t$ (this study)
772.5	68026	%Nps aligned to $\delta(\text{EDC } \delta\text{D})/\delta t$ (this study)

¹Calibrated calendar ages of the core section between 0-98 cm have been accidentally misreported in the Supporting Information of the original publication. Correct ages are listed here.

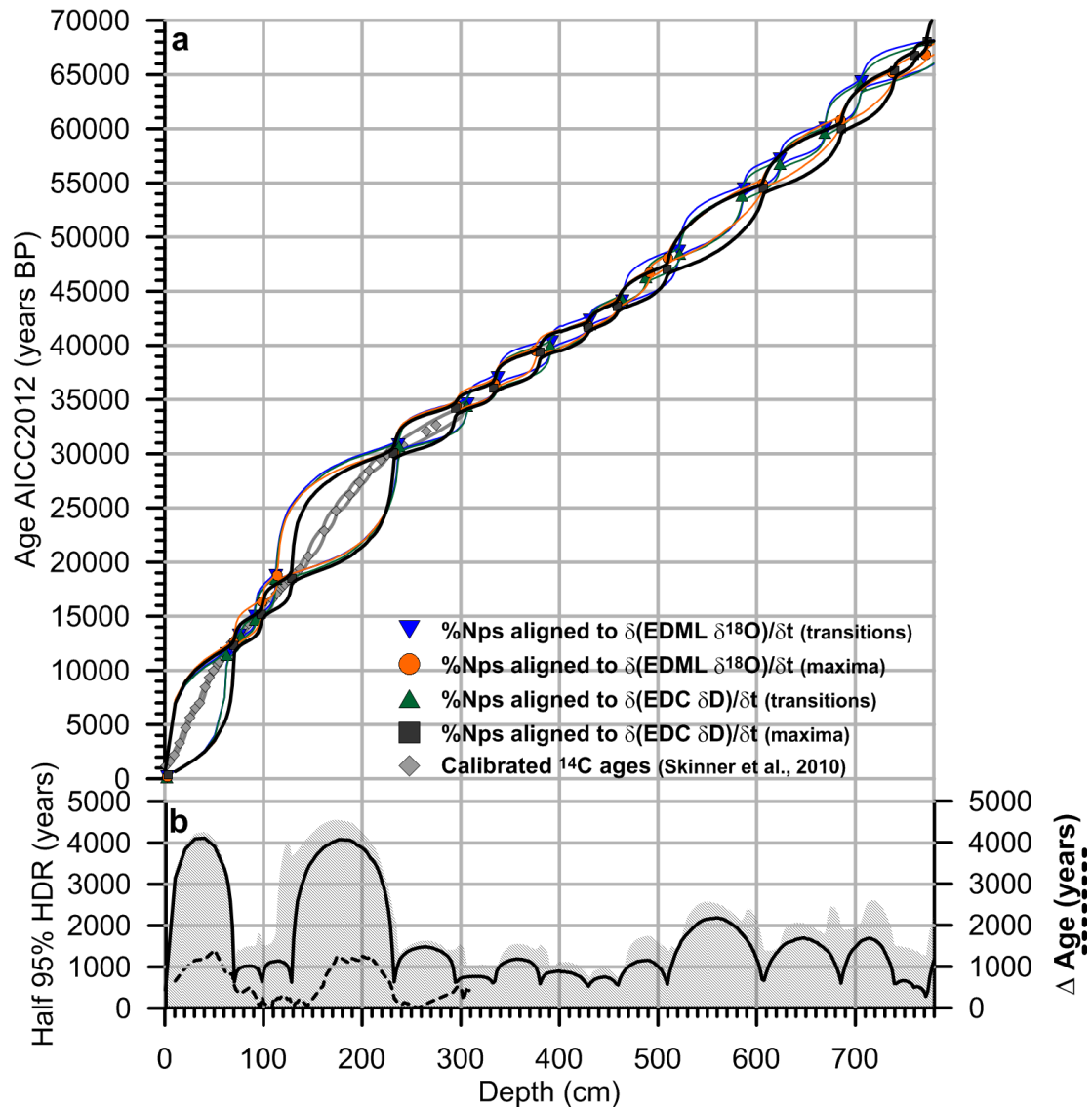


Fig. S1. a) Age-depth markers in sediment core MD07-3076Q derived from calibrated radiocarbon ages (grey diamonds) (Skinner et al., 2010) and the stratigraphic alignment of variations in the abundance of *N. pachyderma* (s.) (%Nps) with the first derivative of the EPICA Dome C (EDC) δD and the EPICA Dronning-Maud-Land (EDML) $\delta^{18}\text{O}$ records on the AICC2012 age scale (Veres et al., 2013) (the alignment of %Nps lows with the maximum rate of change of the EDC and EDML records is respectively shown as dark squares and orange circles; the alignment of %Nps with the rate of change of Antarctic temperature observed in the EDC and EDML ice cores in transitional phases are shown as green triangles and blue inverse triangles, respectively), envelopes highlight the resulting age model uncertainties (95% high posterior density region, HDR) calculated with the Bayesian statistical software BChron (Haslett and Parnell, 2008), b) half of the 95% HDR region of the chronology that is based on the alignment of %Nps lows with maxima of the first derivative of the EDC δD record (black) in comparison to the maximum half 95% HDR region obtained from all alignment approaches (hatched); the difference in absolute ages obtained from the %Nps-based chronology and the radiocarbon-based age model, where they overlap, is shown as stippled line

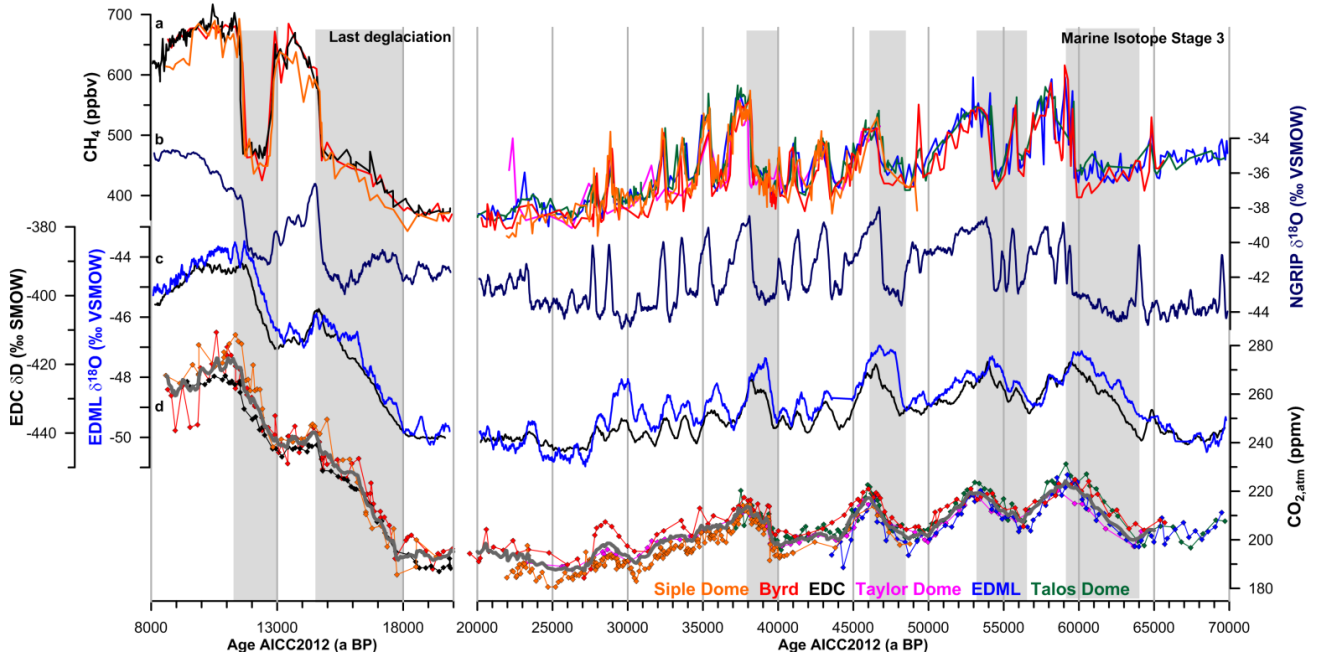


Fig. S2. Compilation of high-resolution atmospheric CH_4 and CO_2 data of the last 70000 years: a) CH_4 concentrations reconstructed from Siple Dome (Ahn and Brook, 2014; Brook et al., 2005), EPICA Dome C (EDC) (Monnin et al., 2001), EPICA Dronning Maud Land (EDML) (EPICA Community Members, 2006), Taylor Dome (Brook et al., 2000), Talos Dome (Buiron et al., 2012) and the Byrd (Blunier and Brook, 2001) ice cores, b) $\delta^{18}\text{O}$ variability of the Greenland NGRIP ice core on the GICC05 age scale (Svensson et al., 2008), which is equivalent to the AICC2012 age scale (Veres et al., 2013), c) δD (grey) and $\delta^{18}\text{O}$ (blue) of the EDC and EDML ice cores (EPICA Community Members, 2006; Jouzel et al., 2007) on the AICC2012 age scales (Veres et al., 2013), d) atmospheric CO_2 ($\text{CO}_{2,\text{atm}}$) concentrations reconstructed from Siple Dome (Ahn and Brook, 2014; Ahn et al., 2004), EDC (Monnin et al., 2001), EDML (Bereiter et al., 2012; Lüthi et al., 2010), Talos Dome (Bereiter et al., 2012), Taylor Dome (Indermühle et al., 2000) and the Byrd ice core (Ahn and Brook, 2008; Blunier and Brook, 2001); the mean $\text{CO}_{2,\text{atm}}$ is marked as a grey line; grey bars show intervals of rising $\text{CO}_{2,\text{atm}}$